Dual-Readout Calorimetry for the ILC

Classification (subsystem)

Calorimeter

Personnel and Institution(s) requesting funding

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University of California at San Diego: H.P. Paar
Iowa State University: J. Hauptman and J. Lamsa

Collaborators

A. Penzo (INFN Trieste, Italy)

Collaborating personnel will work on the project but are not requesting funding here.

Project Leader

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Project Overview

The DREAM (Dual-REAdout Module) calorimeter was developed as a device that would make it possible to perform high-precision measurements of hadrons and hadron jets, while not subject to the limitations imposed by the requirements for compensating calorimetry. The detector is based on a copper absorber structure, equipped with two types of active media which measure complementary characteristics of the shower development. Scintillating fibers measure the total energy deposited by the shower particles, while Čerenkov light is only produced by the charged, relativistic shower particles. Since the latter are almost exclusively found in the electromagnetic (em) shower component (dominated by π^0s produced in hadronic showers), a comparison of the two signals makes it possible to measure the energy fraction carried by this component, f_{em}, event by event. As a result, the effects of fluctuations in this component, which are responsible for all the traditional problems in non-compensating calorimeters (non-linearity, poor energy resolution, non-Gaussian response function), can be eliminated, and an important improvement in the hadronic performance is achieved.

The results of our work so far, details of which are given in the section "Results of Prior Research" demonstrate that the complementary information from dE/dx and from the production of Čerenkov light in the same showers provides a very powerful tool for improving hadronic calorimeter performance. In the proposed project, we would like to study how this principle could be optimally applied in a practical 4π detector for an experiment at the ILC. We want to concentrate on two aspects:

1. The electromagnetic section
2. The readout

The electromagnetic section

The benefits of the dual-readout method are by no means limited to fiber calorimeters. Any medium that generates both Čerenkov light and scintillation light can be used for this purpose. And since the sampling fraction does not have to have a specific value (as in compensating calorimeters), there is no reason why a calorimeter based on the dual-readout principle could not have excellent electromagnetic energy resolution. An attractive and cost-effective option which we would like to investigate is an electromagnetic section consisting of trapezoidal lead-glass blocks doped with an appropriate scintillating agent. The concentration of the dopants and their properties (decay time, spectrum) should be chosen such as to optimize the efficiency with which the scintillation and Čerenkov signals could be separated from each other.

We foresee a three-year program for this part of the project, which will be concentrated at Texas Tech University. In Year 1, we will investigate different dopants and doping techniques. A number of small doped lead glass blocks will be produced and tested, with the electron Van de Graaff accelerator at Texas Tech University. In Year 2, we will build and assemble a full electromagnetic detector based on the chosen, optimized technique. In Year 3, this detector will be combined with the existing DREAM hadron calorimeter, and tested in high-energy particle beams at CERN or Fermilab.

The readout

The fiber-based DREAM calorimeter could in principle form an excellent and cost-effective solution for the hadronic section of a calorimeter system for a Linear Collider experiment. However, the readout of its many fibers would present a substantial challenge. The scintillating fibers and the Čerenkov fibers have to be grouped in separate bunches for readout by their respective light detectors. The prototype that was extensively tested in particle beams was read out with standard photomultipliers (PMTs), two per tower. The grouping of the fibers was labor intensive and required the fibers to extend about 50 cm beyond the end of the calorimeter. While this worked very well in the beam tests, it probably would not scale well with the lateral size of the calorimeter. We propose R&D on a variety of readout techniques to see if we can identify and develop a readout method that is practical and consistent with the requirements of an actual ILC experiment.

To reduce the amount of work required for separating the fibers into bunches, it is clearly advantageous if the bunches can be made as small as possible and be directed to their respective readout elements without too much routing. At the present time, great advantages in that respect seem to be offered by the use of silicon photomultipliers (SiPM).

These devices were developed a few years ago by a group from the Moscow Engineering and Physics Institute, in collaboration with the "Pulsar Enterprise" and the Lebedev Physical Institute. They consist of many (approximately 1000 per mm^2) Si pixels operating in a limited Geiger mode with a gain of 10^6. Each pixel is operated in a binary mode, but because of the high pixel density, each pixel sees on average less than one photon, so that the response is linear. As the number of photons per mm^2 increased, the pixels have to be made smaller to keep the number of photons per pixel less than 1. The current state of the art is 2500 pixels per mm^2, adequate for our purposes. The signals from the pixels are readout by aluminum strips connected to the individual pixels to collect their summed signal. We want to investigate if these strips could be tailored to form readout patches each consisting of many pixels but small enough to accept scintillating or Čerenkov fibers on each patch. There is a trade-off to be made between the number and size of the patches on the one hand and the number of fiber bunches to be made and routed on the other hand.

Published tests (B. Dolgoshein *et al.*, Int. Conf. on New Developments in Photodetection, Beaune, France, June 2002) show that the SiPM have properties similar to the best PMTs in terms of gain, noise, time resolution, and single-photon detection (good for calibration) but they do not require high voltage (tens of Volts are sufficient), can operate in magnetic fields, have better stability under temperature and voltage variations. Their dynamic range (~ 1000) is more limited than for PMTs but adequate for our purposes.

Also for this part of the project, we foresee a three-year program. UCSD will be the lead institution for this part. In Year 1, we will investigate SiPM's properties using light sources. Especially spatial uniformity of response, linearity, spectral respsonse, and stability under voltage and temperature variations are of interest. In parallel and as a possible alternative, we will investigate standard multi-anode PMTs. In Year 2, we will build a small version of the DREAM calorimeter, using existing spare material from the existing project, and equip it with the readout chosen on the basis of the Year 1 R&D. In Year 3, this calorimeter will be tested in high-energy particle beams at CERN or Fermilab.

Broader Impact

This proposal, if funded, will contribute to the knowledge base in our respective Physics Departments. The beneficiaries of that will be postdocs, graduate students, and undergraduate students participating in the research funded in this proposal.

One of us (Hans P. Paar) is co-director of NSF's REU (Research Experience for Undergraduates) program located in UCSD's Physics Department. Through this program, we will recruit undergraduates, generally from disadvantaged backgrounds, to participate in our research program. This includes taking them with us to an accelerator laboratory such as FermiLab or CERN where they can experience first hand the atmosphere of forefront research.

As in the case of the DREAM project, we will involve TTU Quarknet treachers and their highschool students in construction, tests and analyses, where possible.

Faculty will recruit junior and senior undergraduates to participate in our laboratory based research. There they will use the state-of-the-art equipment to which this Grant has contributed.

Undergraduates working in our labs will often present their research at an Undergraduate Research Conference, attended by their peers and faculty supervisors. Here they learn what it means to stand up and present your results and answer questions "on your feet".

Results of Prior Research

This project, known by its acronym DREAM (Dual-READout Module) was started in 2001, with a grant ($150K) received by the project leader in the context of the Advanced Research Program of the State of Texas. In 2002, this grant was supplemented by funds from DOE's Advanced Detector Research program. Since then, the proponents have received a total amount of $340K from the latter source, in four installments.

We have used these funds to construct and test a generic prototype, which was intended to test the dual-readout principles and measure the extent to which the performance of hadron calorimeters could be improved by making use of these principles. The detector is based on a copper absorber structure, equipped with two types of active media which measure complementary characteristics of the shower development. Scintillating fibers measure the total energy deposited by the shower particles, while Čerenkov light is only produced by the charged, relativistic shower particles. The total instrumented mass is 1030 kg (depth 10 $\lambda_{\rm int}$), and the 36,000 fibers are read out by 38 PMT's.

This detector was built in the Physics department of Texas Tech University and then shipped to CERN, where it was tested with high-energy pions, electrons and muons in the H4 beam of the Super Proton Synchrotron. CERN allocated three testbeam periods to this project, during the summers of 2003 and 2004.

The results of these tests are described in a number of papers. Three papers have already appeared in the scientific literature:

- N. Akchurin *et al., Muon Detection with a Dual-Readout Calorimeter*, Nucl. Instr. and Meth. **A533** (2004) 305–321.
- N. Akchurin *et al., Electron Detection with a Dual-Readout Calorimeter*, Nucl. Instr. and Meth. **A536** (2005) 29–51.
- N. Akchurin *et al., Hadron and Jet Detection with a Dual-Readout Calorimeter*, Nucl. Instr. and Meth. **A537** (2005) 537–561.

A fourth paper has been accepted for publication:

- N. Akchurin *et al., Comparison of High-Energy Electromagnetic Shower Profiles Measured with Scintillation and Čerenkov Light*, Accepted for publication in Nucl. Instr. and Meth.

Two other papers are in an advanced state of preparation. The DREAM project was also presented in two talks at the XIth International Conference on Calorimetry in High Energy Physics (Perugia, Italy, 2004). In his summary talk, the speaker called DREAM the most significant new development in calorimetry in recent history. All papers can also be found at the website of the DREAM project: http://www.phys.ttu.edu/dream/

The idea to combine the complementary information from dE/dx and from the production of Čerenkov light has been proven to be a very powerful tool for improving the hadronic calorimeter performance (Figure 1). The performance of our detector is considerably superior to what is commonly achieved with hadron calorimeters used in particle physics experiments. For example, high-energy (200 GeV) jets were measured with a resolution better than 4% (Figure 1b). Because of the limited size (the total instrumented mass of the test module was only 1030 kg), fluctuations in (lateral) shower leakage contributed significantly to the measured resolution. We have shown that if we made use of the fact that the jet energy was known (thus effectively eliminating the contributions of shower leakage to the results), the mentioned resolution could be further improved by a factor of two (Figure 1c). Similar improvements may thus be expected for a detector with a larger instrumented mass than the device tested in this study.

Perhaps even more important is the fact that the (simple) procedure we developed to correct event by event for differences in the electromagnetic shower fraction automatically led to a correct reconstruction of the shower energy, both for jets and for single hadrons, *in an instrument calibrated with electrons*, over the full energy range at which the detector was tested. Anyone who has ever worked with a hadron calorimeter in an experiment will appreciate this very important feature, which is illustrated in Figure 2.

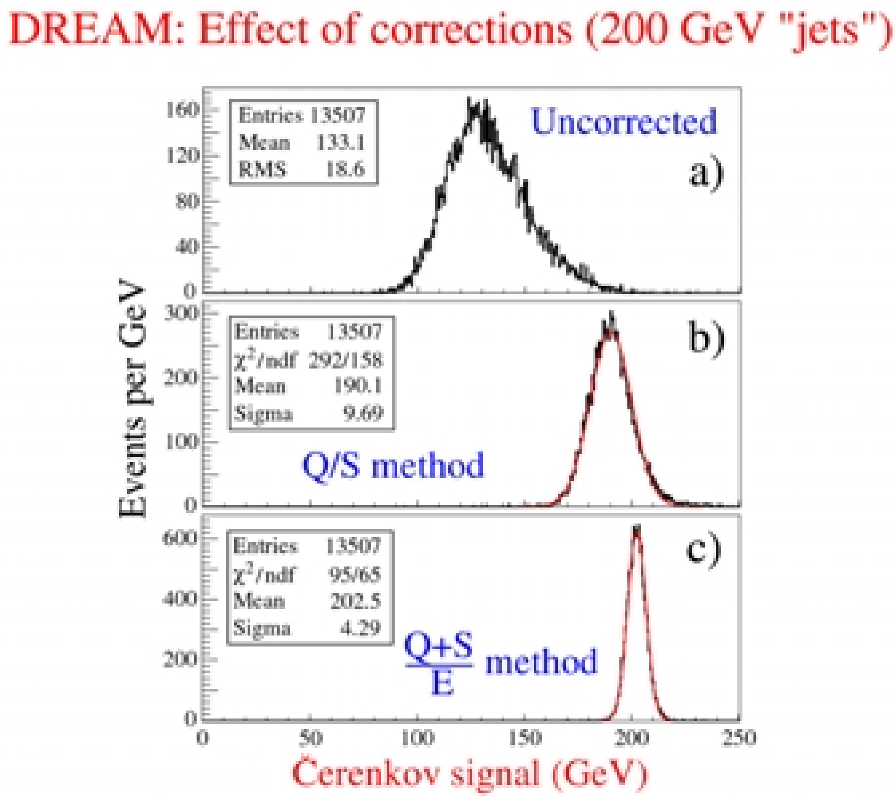

Figure 1: Scintillator signal distributions for 100 GeV π^- in the DREAM calorimeter before any corrections were made(a), after the corrections based on the observed Q/S signal ratio were applied (b) and after, in addition, leakage fluctuations were eliminated (c). See text for details.

In the second stage of this project (DREAM-2) , which was separately reviewed, approved and funded by DOE (2003), we investigated if and to what extent the signals from a medium that generates both scintillation and Čerenkov light can be split into these two components. For these studies, part of the DREAM calorimeter was modified. The fibers from a readout cell were split into three bunches instead of the usual two. These bunches contained only scintillating fibers, only quartz fibers, or a mixture of the two types of fibers, respectively. Different techniques to separate the two types of light were being tried on this mixture, and the quality of the separation could be verified event by event with the "pure" signals.

In order to distinguish between the two types of light, we investigated three different characteristics:

1. The time structure of the signals. Čerenkov light is instantaneous, while scintillation is a process with one or more typical time constants.
2. The directionality of the light. Scintillation light is emitted isotropically, while Čerenkov light is emitted at a characteristic angle with the direction of the superluminous shower particle that generates it.
3. The light polarization. Unlike scintillation light, Čerenkov light is polarized.

A fourth characteristic, the spectral distribution, was not investigated so far, because we did not see an easily applicable method to exploit differences between the spectra of the two types of light generated by this type of calorimeter.

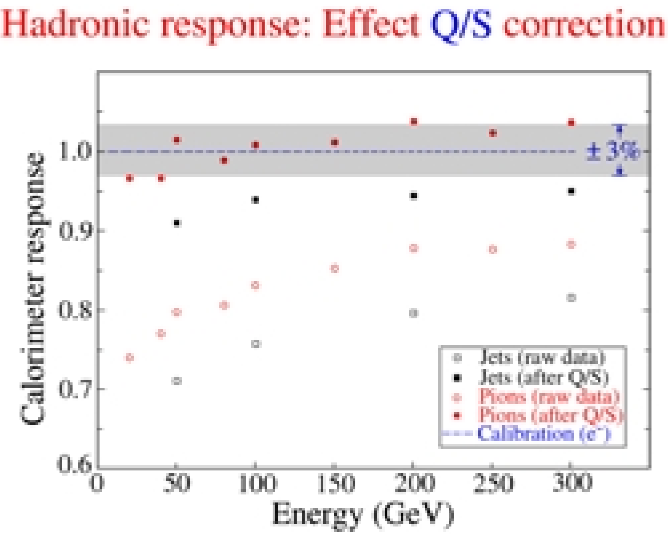

Figure 2: The calorimeter response (average signal per GeV) for single pions and high-multiplicity jets, as a function of energy, before and after corrections made on the basis of the measured Q/S signal ratio. The response is normalized to electrons.

The difference in directionality was exploited by reading the fibers from both ends. The preliminary results are very encouraging. The ratio between the signals measured at both ends of the fiber was found to be more than a factor of 3 smaller for pure Čerenkov light than for pure scintillation light. By measuring this ratio for mixed signals, the composition of the light in that mixture could be determined, event by event. Also the differences in time structure made this possible, as illustrated in Figure 3. Not surprisingly, the measurement of the composition of a given signal was most precise when the relative numbers of scintillation and Čerenkov photons were compatible. At the present time, we are analyzing these and other data collected during the most recent beam tests and expect this to result in at least one additional DREAM publication in the coming year.

Facilities, Equipment and Other Resources

The TTU HEP labs are equipped with generic NIM, CAMAC and VME electronics. Several specialized tools were designed and manufactured for fiber cleaving, polishing and termination during the DREAM project. Some funds for modification and upgrade of this equipment are requested.

Our computer facilities are well-equipped for Monte Carlo calculations and data analyses with the newest versions of the common simulation packages. For bench test measurements, we have adequate data acquisitions systems and electronics as well.

We anticipate using different types of spectrometers for the analyses of light from a variety of active media (scintillation and Čerenkov radiation). We may have to augment our existing spectrometers with different gratings to gain enhanced sensitivity to various wavelength regions.

The TTU HEP lab operates a 2-MeV electron Van de Graaff that we used extensively in the early stages of fiber selection for the DREAM project. We anticipate using this versatile accelerator in the initial phases of these studies.

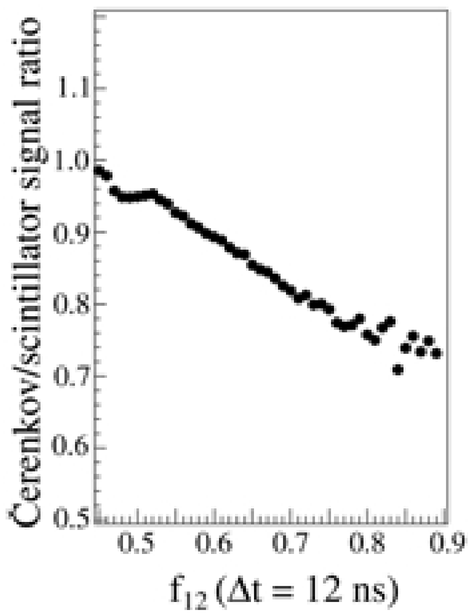

Figure 3: The relationship between the measured ratio of the Čerenkov and scintillator signals from 100 GeV "jets", and the percentage of the signal that was recorded in the tail, *i.e.* more than 12 ns after the start. Preliminary results.

It is important to note that this proposal builds on a recent successful R&D program (DREAM). This has several positive implications:

- The absorber, standard scintillating and Čerenkov (quartz and clear plastic) fibers, and photomultipliers already exist.
- The proponents of this proposal have invested many years developing new calorimeter techniques and have been very effectively working as a single team.
- The two proposals (*Dual-Readout Calorimetry for ILC* and *Ultimate Hadron Calorimetry*) we submit in this context for consideration are tightly coupled in all kinds of resources.

All of the above provide a unique and proven synergy.

FY2005 Project Activities and Deliverables

In 2005, we plan to investigate different dopants and doping techniques. A small number of doped lead glass blocks will be produced and tested, with the electron Van de Graaff accelerator at TTU. We will also investigate relevant SiPM's properties using light sources. Especially spatial uniformity of response, linearity, spectral respsonse, and stability under voltage and temperature variations are of interest to this project. In parallel and as a possible alternative, we will investigate standard multi-anode PMTs. Where possible, results from these two readout systems will be compared.

FY2006 Project Activities and Deliverables

We anticipate building a full size electromagnetic calorimeter based on the chosen and optimized doping technique. If this module is ready in time, high-energy beam tests may also be carried out. We will build a small version of the DREAM calorimeter and equip it with the readout chosen on the basis of the Year 1 R&D.

FY2007 Project Activities and Deliverables

We plan a combined electromagnetic and hadronic prototype test at a high-energy particle accelerator. A new fully sampling em calorimeter followed by the existing DREAM hadron calorimeter, possibly equipped with three different types of fibers, will be exposed to beams of electrons, hadrons and "jets". The new small DREAM-like module, equipped with the new readout, will also be tested, in electron beams.

Budget justification: Texas Tech University will be the lead institution in this project. We plan to use professional expert assistance in scintillator dopants and doping techniques (∼9K$). We plan to involve undergraduate students as the project develops. The fringe benefits rate is assumed to be 25% on salaries and the salary expenditure with fringe benefits is ∼16K$.

Equipment, materials and supplies will dominate the cost of this project.

We assumed no overhead charge on equipment and travel. A similar agreement was reached with the TTU Office of Research Services for previous grants of this type. TTU will charge overhead on salaries at the off-campus rate (26.5%).

TTU will subcontract the University of California at San Diego and Iowa State University. Separate tables for these subcontracts are shown below.

Three-year budget, in then-year K$

Institution: Texas Tech University

Item	FY2005	FY2006	FY2007	Total
Other Professionals	3.0	3.0	3.0	9.0
Graduate Students	0	0	0	0
Undergraduate Students	0	2.0	2.0	4.0
Total Salaries and Wages	3.0	5.0	5.0	13.0
Fringe Benefits	0.8	1.3	1.3	3.3
Total Salaries, Wages and Fringe Benefits	3.8	6.3	6.3	16.3
Equipment	0	5.0	8.0	13.0
Travel	5.0	10.0	10.0	25.0
Materials and Supplies	10.3	30.0	11.1	51.4
Other direct costs	0	12.1	8.0	20.1
UC-San Diego subcontract	20.0	40.0	20.0	80.0
Iowa State U subcontract	10.0	15.0	15.0	40.0
Total direct costs	49.1	118.3	78.3	245.7
Indirect costs	1.0	1.7	1.7	4.3
Total direct and indirect costs	50.0	120.0	80.0	250.0

Budget justification:

University of California at San Diego will concentrate on new readout techniques, particularly SiPMs. In Year 2, investment in electronics design is expected. Throughout this project, a modest expenditures are planned to purchase SiPMs and related hardware. Similarly, small amount funds are forseen for travel for group meetings and beam tests.

Three-year budget, in then-year K$

Institution: University of California at San Diego

Item	FY2005	FY2006	FY2007	Total
Other Professionals	0	18.5	0	18.5
Graduate Students	0	0	0	0
Undergraduate Students	0	0	0	0
Total Salaries and Wages	0	18.5	0	18.5
Fringe Benefits	0	3.1	0	3.1
Total Salaries, Wages and Fringe Benefits	0	21.7	0	21.7
Equipment	7.4	3.0	6.0	16.4
Travel	5.0	5.0	6.1	16.1
Materials and Supplies	5.0	2.7	5.0	12.7
Other direct costs	0	0	0	0
Total direct costs	17.4	32.4	17.1	66.9
Indirect costs	2.6	7.6	2.9	13.1
Total direct and indirect costs	20.0	40.0	20.0	80.0

Budget justification:

Iowa State University has a long track record in detailed calorimeter simulations. John Hauptman will partially fund a graduate student (3 months out of a year) for three years. A modest amount of travel funds are required to travel to meetings and beam tests.

Three-year budget, in then-year K$

Institution: Iowa State University

Item	FY2005	FY2006	FY2007	Total
Other Professionals	0	0	0	0
Graduate Students	5.0	5.0	5.0	15.0
Undergraduate Students	0	0	0	0
Total Salaries and Wages	5.0	5.0	5.0	15.0
Fringe Benefits	1.3	1.3	1.3	3.8
Total Salaries, Wages and Fringe Benefits	6.3	6.3	6.3	18.8
Equipment	0	0	0	0
Travel	2.1	7.1	7.1	16.3
Materials and Supplies	0	0	0	0
Other direct costs	0	0	0	0
Total direct costs	8.3	13.3	13.3	35.0
Indirect costs	1.7	1.7	1.7	5.0
Total direct and indirect costs	10.0	15.0	15.0	40.0